

Quark-Hadron Phase Transition with Finite-Size Effects in Neutron Stars[†]

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Abstract We study the quark-hadron phase transition with the finite-size effects in neutron stars. The finite-size effects should be, generally, taken into account in the phase transition of multi-component system. The behavior of the phase transition, however, strongly depends on the models for quark and hadron matter, surface tension, neutrino fraction, and temperature. We find that, if the surface tension is strong, the EOS becomes similar to the case of a Maxwell construction for any hadron and/or quark model, though we adopt the Gibbs conditions. We also find that the mass-radius relations for that EOS are consistent with the observations, and our model is then applicable to realistic astrophysical phenomena such as the thermal evolution of compact stars.

Key words equation of state—stars: neutron stars, magnetars

1. INTRODUCTION

The equation of state (EOS) is one of the most important topics in studies on neutron stars. But there is a large uncertainty in the finite-density region of the EOS. One way of advancing our understanding of the EOS of neutron stars (NSs) is to study baryon-

[†] This work was supported by JSPS KAKENHI Grant Numbers 25105510, 23540325, 24105008.

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baryon(BB) interactions by Lattice QCD (LQCD) simulations [1], another to perform experiments such as heavy-ion collisions at JPARC. Since the quantum-many body methods, such as variational principle [2, 3, 4], Brueckner-Hartree-Fock(BHF) theory [5, 6, 7] and Dirac-Brueckner-Hartree-Fock theory [8], which reveal the EOS for NSs using BB interaction directly are applicable only to hadron matter, there is the need for developing methods to investigate the possible the existence of exotic matter such as quark matter in NSs [9].

In this study, we consider nucleon and quark degrees of freedom, and study the mixed phase of the quark-hadron phase transition in NSs. The details are given in Refs. [10, 11, 12].

2. OUR MODELS AND NUMERICAL RESULTS

We adopt the BHF theory for hadronic matter [5, 6] with the Bonn B potential [13]. New potentials could be employed when LQCD simulations and/or experiments would reveal them. For the quark matter we adopt a non-local NJL model [14, 15] with vector coupling. In Fig. 1 we show results using for the ratio of the vector and the scalar channel couplings $\eta_V = G_V/G_S = 0.20$.

Note that the phase transition itself has large uncertainty [16] which comes mainly from *finite size effects*, where inhomogeneous structures appear depending on the balance between surface tension and Coulomb interaction [10, 17]. We assume a sharp boundary between quark and hadron matter, with values for the surface tension parameter $\sigma=10$ MeV fm⁻² and $\sigma=40$ MeV fm⁻², and discuss the effects of its variation as in our previous studies with a simple quark model [15,16].

The numerical results for the EOS with quark-hadron phase transition are shown in Fig. 1. In this figure, it is shown that the strong surface tension ($\sigma=40$ MeV fm⁻²) makes the phase transition similar to the Maxwell construction one. This behaviour is general since it is also found in the simple bag model [10, 18, 19]. We obtained mass-radius relations for our EOS with maximum masses M_{max} consistent with the observational results [20, 21], i.e., $M_{max} = 2.47$ (2.49) M_\odot for $\sigma = 10$ (40) MeV fm⁻² and $\eta_V = 0.20$. The radii of NSs in our models are 12-14 km.

3. DISCUSSION AND FUTURE WORKS

We do not consider the hyperons, since their appearance is likely prevented by that of quarks [15,16]. We plan to investigate different quark models and to take into account further degrees of freedom in the mixed phase as, e.g., hyperons.

ACKNOWLEDGEMENTS NY likes to express hearty thanks to the organizers on the conference “*Quarks and compact stars 2014*” for their warm hospitality, DB acknowledges support by NCN grant UMO-2011/02/A/ST2/00306. This work was supported in part by the COST Action MP1304 “NewCompStar”.

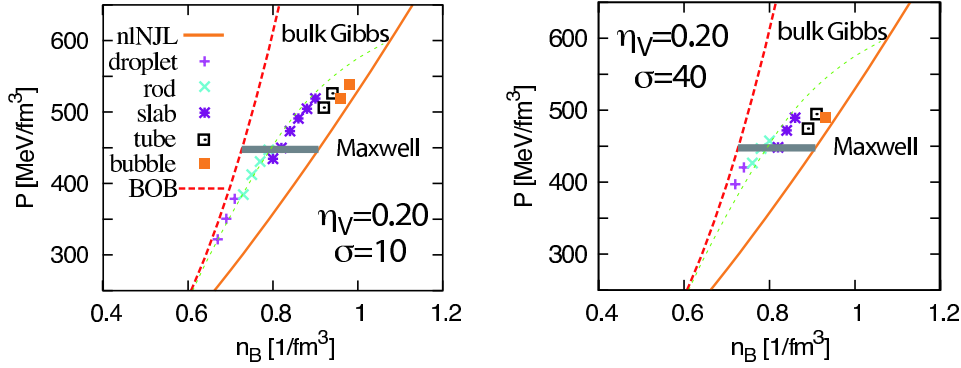


Fig. 1 EOS with quark-hadron phase transition shown as pressure vs. baryon number density with pure quark matter from non-local NJL model (solid lines), pure hadron matter by BHF with Bonn B potential (dashed lines) and the extreme cases of mixed phase by bulk Gibbs condition (dotted lines) and Maxwell construction (bold solid lines). Each dot shows the mixed phase considering *finite size effects*, where inhomogeneous structures, such as droplet, rod, slab, tube (anti-rod), bubble (anti-bubble), appear. The mixed phase appears from the onset density 0.67 (0.70) fm^{-3} to 1.00 (0.97) fm^{-3} for $\sigma = 10$ (40) MeV fm^{-2} and $\eta_V = 0.20$.

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